Figure 1. Don Jennings, section chief, Quantum Electronics, NIST (1965).

Pulsed-Laser Metrology at NIST

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Lasers and laser metrology have become an important part of our daily lives. Since the inception of the first operable laser 41 years ago,[1] there has been explosive growth in the number of new applications of laser technology: from supermarket scanners to vision correction procedures, applications range from the mundane to the remarkable. Important new advances, such as breaking up blood clots in stroke patients, are being discovered every day.[2]

Since the introduction of the first laser energy standard by Jennings[3] in 1966 (see Fig. 1), the National Institute of Standards (NIST) has worked closely with industry to develop standards and appropriate measurement techniques to characterize laser radiation. In the 1960s, laser safety considerations, rather than a need for improved measurement accuracy, often drove demands for laser power and energy measurements. However, by the early 1970s, commercial customers included laser manufacturers who required power and energy calibrations for laser classification purposes. Early safety-conscious customers also included supermarket scanner manufacturers.

As new laser applications continue to develop, measurement accuracy has become an even more critical issue. Demands for improved accuracy have led to new NIST laser standards and measurement techniques,[4] as well as to increasing diversity of the group of calibration customers. The NIST laser calibration services support a variety of detectors, including thermal and semiconductor devices, and span a wide range of laser powers and energies (see Table 1). The NIST customer base now includes detector and laser manufacturers around the world: standards laboratories, research facilities, military sites, and laser instrument manufacturers.

Over the past three years, the number of calibration requests for excimer laser measurements alone has more than doubled. As a result of this increasing demand, a substantial portion of NIST's laser measurement efforts is now focused on excimer laser measurements. Due to the complexity and cost of establishing laser sources and developing primary standards, today NIST is the only national laboratory in the world to offer excimer laser measurement services.

Excimer lasers emit ultraviolet radiation with large pulse energies and short pulse widths that lead to high peak powers. Long-term exposure to high peak powers, large pulse energies, and high photon energies cause most conventional optical materials to degrade. At wavelengths below 200 nm, the environmental conditions of the measurement system are also an issue. For example, light is strongly absorbed by oxygen molecules in the air at these short wavelengths, resulting in ozone generation. Consequently, it is important to specify the oxygen content of the measurement environment when reporting the results for these calibrations.

Laser Power and Energy Calibrations

	Laser	Wavelength	Range
CW	Argon Ion	488 and 514 nm	1 μW ~ 1W
	He–Ne	633 nm	1 μW ~ 20 mW
	Diode	830 nm	100 μW ~ 20 mW
	Nd:YAG	1064 nm	100 μW ~ 450W
		1319 nm	100 μW ~ 10 mW
	HeNe	1523 nm	100 μW ~ 1 mW
	CO_2	10.6 μm	1 μW ~ 1kW
Pulsed	KrF Excimer	248 nm	10^{-3} ~ 200 mJ per pulse 50 μW ~ 9W average power
	ArF Excimer	193 nm	10^{-3} ~ 3 mJ per pulse 50 μW ~ 3W average power
	Nd:YAG	1064 nm	1 ~ 50 mJ per pulse 10 nW ~ 100 μW 10^{-3} ~ 10 nJ per pulse

Table 1. NIST calibration services table.

Excimer lasers are used in a wide range of industrial applications, including optical lithography for semiconductor manufacturing, vision correction procedures, laser marking, and micro-machining of small structures such as ink jet printer nozzles. This article will concentrate on the area with the largest demand for accurate measurements: laser metrology for optical lithography.

Information technology has fueled demand for faster logic circuits and computer chips with higher memory densities. In the early 1990s, this led to the introduction of deep ultraviolet (DUV) laser-based lithographic tools for semiconductor manufacturing. These tools, which now employ KrF (248 nm) and ArF (193 nm) excimer lasers, have boosted the need for accurate excimer laser measurements. As a result, NIST, with SEMATECH* support, has developed primary standard calorimeters and measurement services for both 193 nm and 248 nm excimer laser power and energy calibrations.[4,5,6] A standard calorimeter for use at 157 nm is under development to support the next generation of photolithography tools.

A number of laser measurements are important for photolithography tool development and performance. Measurements near the laser source are used as part of a feedback mechanism to stabilize the source's pulse energy. There is also an optimum laser dose (i.e., energy density) at the wafer plane that provides the best resolution of small features. Imagine a photograph: overexposure or underexposure of the film leads to reduced image contrast and poor resolution. In addition to laser power and energy measurements, optical material characterization measurements such as transmittance and birefringence are also critical for tool design and performance.

* SEMATECH, the semiconductor manufacturing technology group, was originally formed as a research consortium of U.S. semiconductor manufacturers and their suppliers. The purpose of the consortium was to reinvigorate the U.S. semiconductor industry and allow it to compete in the global marketplace. (See http://www.sematech.org for more information.)

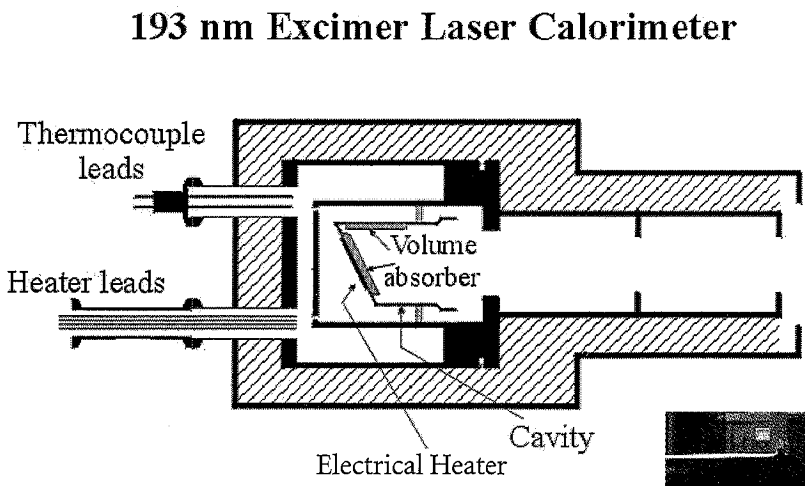


Figure 2. Schematic drawing of NIST 193 nm calorimeter.

Laser power and energy measurements

The excimer laser power and energy calibration facilities are conceptually similar to other pulsed-laser calibration facilities at NIST. During a calibration procedure, detectors under test are compared against primary standards in a standard beamsplitter-based optical delivery system.

Primary standards

Electrically calibrated calorimeters are used as primary standards for most of NIST's laser power and energy measurements. These calorimeters provide a means for comparing optical energy to electrical energy. A schematic cross-sectional view of the NIST 193 nm calorimeter is shown in Fig. 2. The calorimeter consists of a cavity surrounded by a temperature-stabilized jacket that provides a constant temperature environment. Light enters the calorimeter and impinges sequentially on two pieces of UV-absorbing glass, converting optical energy into thermal energy. The heat is distributed over the entire volume of the absorbing glass to avoid high peak pulse energies damaging the absorbers.

Thermocouples, connected in series and attached to the cavity, record the temperature difference between the cavity and the constant temperature jacket. An electrical heater, located at the rear of the cavity, characterizes the thermal response of the calorimeter as a function of injected electrical energy. Consequently, the calorimeter's response is traceable to electrical units. A key element of this design is the selection of absorbing materials: they must have an appropriate absorption coefficient and a high damage threshold, be stable with time, and not fluoresce appreciably.

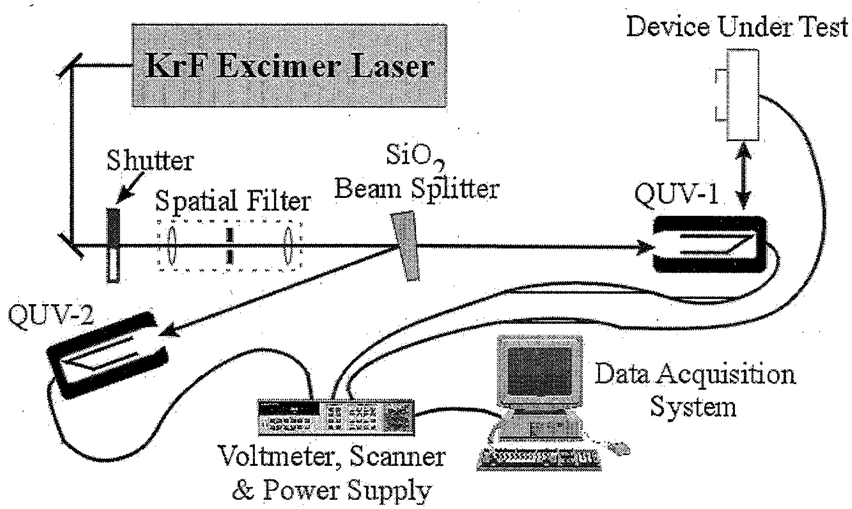
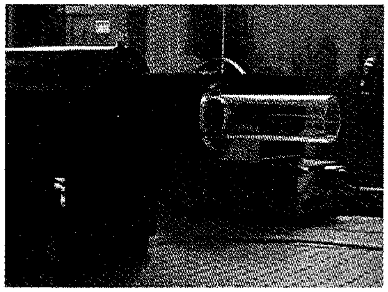


Figure 3. KrF excimer laser measurement system.



Laser measurement system

The KrF measurement system, operating at 248 nm, is conceptually similar to all of the NIST laser measurement systems (see Fig. 3). A fused silica beamsplitter, located in the beam path, transmits most of the light into the first standard (identified in Fig. 3 as QUV-1). A portion of the beam is reflected toward the second standard (shown in Fig. 3 as QUV-2).

Beamsplitter-based systems allow researchers to monitor energy during the course of the measurement and to extend the limits of the useful energy range of the calibration measurements. During the calibration process, detectors under test are substituted for either standard depending on the desired energy level. This direct substitution method allows the device under testing to be compared with the NIST primary standards. The overall measurement uncertainty of this system was recently reduced to 1%, from 2%. NIST is investigating methods to reduce uncertainty again by a factor of two.

Optical material characterization measurements

To supplement its laser power and energy measurement services, NIST is developing the capability to measure laser transmittance and optical birefringence of UV optical materials. Birefringent materials (in which the two orthogonally polarized components of light propagate at different speeds) can adversely effect the resolution of a DUV lithography tool. Birefrin-gence can be an inherent property of the material or it can be induced by mechanical stresses placed on it—a situation common in the semiconductor lithography process. A plot of the stress-optical coefficient (the amount of retardance introduced per unit stress, as a function of wavelength for fused silica) is shown in Fig. 4.[7,8]

Measurements of stress-optical coefficients and birefringence are made using He–Ne lasers operating in the visible wavelength region. NIST has initiated a two-pronged effort to provide UV birefringence measurements and to develop a two-dimensional (2D) imaging polarimeter. This will allow NIST to pinpoint spatial birefringence non-uniformities in photomasks and to provide absolute retardance measurements at appropriate UV wavelengths.

In 1998, NIST established a laser-based transmittance measurement service at 193 nm to help resolve observed discrepancies between laser- and lamp-based transmittance measurements. At short wavelengths, a surface cleaning process occurs when samples are exposed to intense laser light.[9] Particularly in a tool that may contain as many as 30 optical elements, it is therefore important to measure the transmittance of the individual elements in the same manner in which they will be used.

In conclusion, pulsed-laser measurements are critical in a variety of manufacturing situations, including process control, improved yields, and laser safety. To conserve NIST's leadership role in laser metrology well into the future, research efforts aimed at acquiring more accurate laser measurements are underway. Expanded laser measurement services will include new wavelengths and materials characterization measurements for the semiconductor industry.

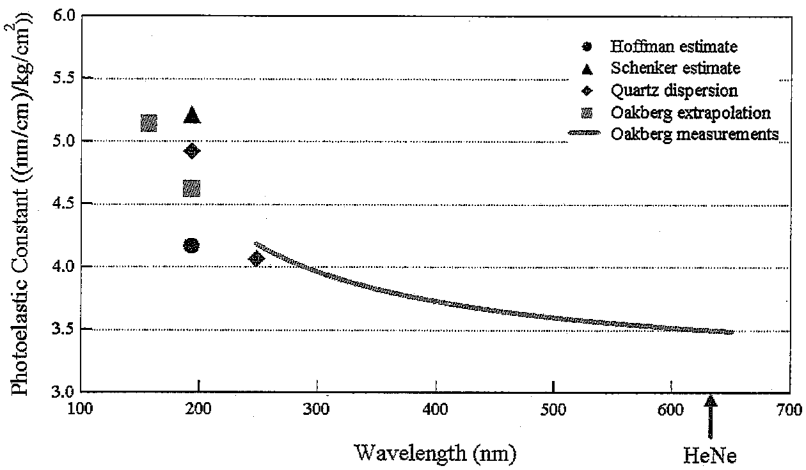


Figure 4. Stress-optical coefficient of fused silica as a function of wavelength.

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